

# ADS-B surveillance experimental deployment using SWIM

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*This paper describes an ADS-B implementation for air-to-air and ground based experimental surveillance within a prototype of a fully automated ATM system, under a trajectory based operations paradigm, and using an air-inclusive implementation of SWIM (System Wide Information Manager). The relations between airborne and ground surveillance are detailed, and the prototype surveillance systems and their algorithms described. Performance is analysed, based both on simulated and real data. The paper also describes the evaluation procedures.*

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## I. INTRODUCTION

Automatic Dependent Surveillance-Broadcast (ADS-B) [3][4][5] is a key enabler for all future Air Traffic Management (ATM) proposals. ADS-B, with the additional deployment of other surveillance sensors such as Wide Area Multilateration (WAM) Systems and Mode S radar, will progressively phase out current Secondary Surveillance Radars. ADS-B may be complemented by Traffic Information System-Broadcast (TIS-B)[6], to enable airborne surveillance of non ADS-B equipped aircraft.

The research described in this paper has been performed within ATLANTIDA, a large Spanish project aiming at implementing a completely automatic prototype of a future Trajectory Based Operation (TBO) ATM system with Unmanned Aircraft Systems (UASs), including both airborne equipment (Navigation, Automated Flight Management, Flight Control, Airborne Surveillance, etc.) and ground functions (Navigation support, Automated Traffic Management, Ground Surveillance, Communication Management, Remote Flight Management, User Operation Centre, Traffic Flow Management, etc.). A significant novelty in ATLANTIDA is the integration of such a system within an air-inclusive SWIM (System Wide Information Management) middleware connecting all ATM systems. This SWIM concept, also present in SESAR [1] and NEXTGEN [2], assumes that all data interchange and information retrieval demands are performed using a unique communication and middleware infrastructure. So, in ATLANTIDA, ADS-B was implemented over a SWIM network comprising both ground and airborne equipment. ATLANTIDA SWIM

was composed of two modes of operation: request-reply, implemented using CORBA procedures, and publish-subscribe, using DDS. This allowed for a flexible implementation of the communication protocols and functionalities based on commercially available middleware, with the following potential advantages over current ADS-B implementations:

- Use of shared communication equipment for all air-to-ground communications, with support for quality of service (QoS) management (latencies, priorities) using a high bandwidth communication channel. ATLANTIDA system relies on Microhard® UHF modems, using FHSS modulation in the 902-928 MHz band, with a resulting 1.2 Mbps data rate, and TDMA protocols, controlled by the ground station modem. It allowed for free experimentation on communication protocols, although an operational implementation would surely need the reuse of current ICAO standardized communications bands.
- Capability to use compressed and encrypted communication means, enabling safer provision of aircraft kinematic state to ground and to nearby aircraft, and optimal exploitation of communication bandwidth.
- Definition of an easily upgradeable communication means, where interchanged data may be modified by a redefinition of the messages using a simple template mechanism (\*.idl files), and automatic regeneration of executable programs, while protocols may be changed by simple QoS changes or software modifications.

The designed ADS-B/TIS-B based surveillance is based on this SWIM concept, being a software-based solution using standard hardware and middleware, while current approaches are based on the use of certified data-buses and hardware, or specific protocols in ground such as ASTERIX. The design covers both the air and ground surveillance segments.

Regarding ground surveillance, it is a complete system with all the typical surveillance functions (measurement association, track initiation and deletion, measurement filtering, integrity tests to increase reliability, etc.) and additional procedures for computational load management. It has been implemented using a modified AIRCON® data processing station, based on Linux middleware with specific wrappers to enable their integration in ATLANTIDA-SWIM. The system is partially implemented in C++ (for the communication and ATLANTIDA ADS-B data processing procedures) and ADA (for the rest of AIRCON facilities, including multisensor data processing, display management and user interface). In ATLANTIDA, all experiments were conducted only with ADS-B data, although AIRCON is capable of processing also radar and WAM data. In fact, the expertise gained in ATLANTIDA has been used to enhance the operational AIRCON surveillance data processing, extending it to process current WAM and ADS-B messages.

ADS-B/TIS-B based air surveillance, with a functionality similar to ground surveillance, has also been implemented. It has stringent computational requirements due to the fact that it is implemented in a mobile platform: it is part of the software included in the airborne embedded PC with Real Time Linux in charge of Flight Management and Flight Control. It is a completely new implementation of ADS-B/TIS-B based

surveillance through a multithreaded application developed using C++, whose communication middleware is based on RTI® DDS implementation [10], and ATLANTIDA SWIM libraries.

ATLANTIDA ADS-B/TIS-B can be seen as an extension of current ADS-B and TIS-B protocols. New data formats have been defined, taking into account the new necessities of TBO and automated ATM. One of the key elements of this kind of operations is the need for very accurate medium term trajectory predictions. Our ADS-B design enables the provision of on-board meteorological measurements to a ground facility, to enable high quality tuning of meteorological models. Another important element of TBO is the capability to interchange trajectory information among different ATM actors. In ATLANTIDA, it is performed using the concept of Aircraft Intent [11]. The broadcasting of aircraft intent information is done through ADS-B to support extensions of ATLANTIDA concept to ASAS (Airborne Separation Assurance Systems), where each aircraft could change their trajectory on the basis of surrounding aircraft intended trajectories.

An important requirement of the whole surveillance infrastructure described in this paper is its capability to be used both for simulation and for experimentation in real flights.

The rest of the paper is organized as follows. Section II contains an introduction to current ADS-B and TIS-B technologies, focused in the information they can interchange and on the protocols used for this communication. Section III describes the relation of air and ground surveillance systems with other avionic and ATM systems. Section IV describes the new data formats and protocols to be used in ATLANTIDA, while sections V and VI describe the internal air-to-air and ground surveillance systems structure and algorithms. Then, the paper describes the experimental and simulation deployment used for the evaluation of the system and Section VIII describes the simulation and real data results. Finally, Section IX includes some conclusions on ATLANTIDA ADS-B implementation and some future research lines.

## **II. CURRENT ADS-B AND TIS-B IMPLEMENTATIONS**

Mode S squitter (also known as 1090 ES) is currently the most used ADS-B implementation. In fact, both SESAR [1] and NEXTGEN [2] take an approach of concentrating efforts on this technology, which can be installed and updated with minor changes into currently mandatory Mode S transponders (for a great part of the aircraft fleet). The different messages available and their fields are described in ICAO Annex 10 [3]. All squitters contain unique ICAO address (Mode S) code identifying unequivocally the transponder/aircraft. The kind of information provided is basically kinetic (position, velocity). There are mainly two kinds of protocols in Mode S squitter: based on quasi-periodic broadcast of messages, for most types of messages; and based on event driven broadcast of messages. They use a shared communication channel that may lead to a high amount of message collisions, effectively reducing nominal measurement period from 1 second.

VDL Mode 4 [5] is a VHF data link technology, also standardized by ICAO, and designed to support CNS/ATM digital communications services. In the Surveillance Domain it was investigated as a candidate ADS-B data link (in complement to 1090 ES) to support ADS-B applications. It provides means for the periodic transmission of quite a lot of kinematic and intent related information potentially using broadcast, multicast, or addressed communication procedures. It can also define event driven procedures for the

transmission of data. It is based on a TDMA process potentially managed by the own airborne radio stations (Self Adaptive TDMA).

The UAT system [4] is specifically designed for ADS-B operation. UAT has lower cost and greater uplink capacity than 1090 ES. UAT does not only provide ADS information: users have access to ground-based aeronautical data and can receive reports from surrounding traffic (using FIS-B and TIS-B protocols). In the United States the UAT link is intended for general aviation aircraft. From a controller or pilot standpoint, the two links operate similarly. Each aircraft broadcasts UAT ADS-B Messages once per second to convey kinetic state and other information.

Finally, TIS-B is the broadcast of traffic information to ADS-B-equipped aircraft from ADS-B Ground based stations. The sources of this information are air traffic surveillance radars or other surveillance sensor such as Wide Area Multilateration (WAM). TIS-B is intended to provide ADS-B-equipped aircraft with a complete traffic picture in situations where not all nearby aircraft are equipped with ADS-B. There are implementations and research on TIS-B based on the three previous technologies (Mode S squitter, VDL [6] and UAT).

Although not properly ADS/TIS-B, there are other surveillance technologies directly related to ADS-B. These are the surveillance technologies related to ADS-C (ADS – Contract [7], as FANS-1), Mode S datalink applications [3] and Airborne Collision Avoidance System (ACAS [3]). These surveillance technologies are based on the data contained within the Mode S transponder or navigation system. The definition of ATLANTIDA surveillance messages and modes of operation also took into account the information provided by these systems.

### **III. ATLANTIDA SURVEILLANCE DESCRIPTION**

ATLANTIDA Surveillance infrastructure is based on the definition of two interrelated systems, one deployed on airborne platforms (SURAIR), and another one compiling data from all aircraft on ground (SURGND). Fig. 1 shows the main relations between SURAIR and SURGND systems and surrounding ATLANTIDA systems.

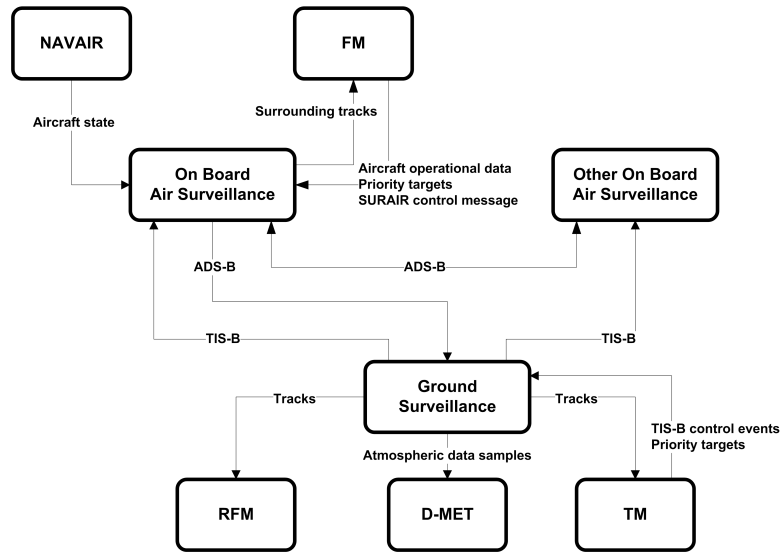


Fig. 1. Overall ATLANTIDA Surveillance architecture

There are two main roles of SURAIR: ADS-B message compilation and broadcasting, which enables the rest of the surveillance functions; and creation of a local air picture situation, to be potentially used by air automation systems. In this second role, its main data sources are nearby aircraft air surveillance for ADS-B and ground surveillance for TIS-B, and its main information consumer is the Flight Manager (FM), which could provide this information, integrated with trajectory information, to other subsystems.

The main role of ground surveillance (SURGND) in ATLANTIDA is to create an air picture situation to be used by the ground ATM system. Its main data source is SURAIR (although the system might exploit other sensors information), and its main data consumer is the Traffic Manager (TM), which provides this information, integrated with trajectory information, to other subsystems, and also performs negotiation of trajectories with aircraft, automated conflict detection and resolution procedures, etc. SURGND also provides traffic information (tracks) to a Remote Flight Manager (RFM), which can act as a means for the remote control of the vehicle. It also provides meteorological samples to the Meteorological system (called DMET) to enable accurate meteorological modelling. Finally, it provides SURAIR with TIS-B data of aircraft, and it can manage TIS-B data rate.

In order to perform time-synchronized hybrid simulations for experimentation, all those systems are connected to a simulation/experimentation control engine. Additionally, they have means for data recording, enabling later simulation/experimental analysis.

#### IV. ATLANTIDA ADS-B AND TIS-B MESSAGES AND PROTOCOLS

ATLANTIDA ADS-B and TIS-B data formats are an extension of the available ADS-B and TIS-B formats to include new parameters of interest for short term and medium term trajectory prediction. They are:

- Aircraft mass.
- Intent information, in a much more detailed format than previous systems [11].

- Attitude information
- Aerodynamic configuration (Flaps, Landing Gear and Speed Brakes state)

Table 1 describes ATLANTIDA ADS-B and TIS-B data formats. Common fields appear in all messages.

Table 1. Message formats

Message	Field	Description
<b>Common fields</b>	<b>callsign</b>	Identification of the aircraft
	<b>time</b>	Time of application of the message
<b>adsb_intent</b>	<b>initial_conditions</b>	Initial conditions are needed to calculate the predicted trajectory based on the aircraft intent
	<b>intent</b>	Intent information. It is a complex field describing the contracted trajectory in a reproducible manner
<b>adsb_kinetic</b>	<b>kinetic_state</b>	Includes 3D geodetic position, groundspeed, heading, attitude (Euler Angles), barometric height
	<b>performance_cat</b>	ADS-B performance categories, such as NIC, NAC or SIL
<b>adsb_meteo</b>	<b>static_pressure</b>	Static Pressure
	<b>temperature</b>	Outside Temperature in aircraft position
	<b>wind_speed</b>	3D wind vector
<b>adsb_status</b>	<b>mass</b>	Full aircraft plus payload plus fuel mass
	<b>configuration</b>	Aerodynamic configuration
<b>tisb_kinetic</b>	<b>kinetic_state</b>	Includes 3D geodetic position, groundspeed, heading, barometric height
	<b>performance_cat</b>	Synthetic ADS-B performance categories, such as NIC, NAC or SIL

Another key difference with other ADS-B implementations is the use of much higher resolution fields for the representation of measurements, so that quantification errors are negligible.

ADS-B/TIS-B protocols are implemented with SWIM middleware making use of publish-subscribe paradigms based on DDS. All messages are provided to their consumers periodically, with means to control the data rate, and therefore the overall communications load. Those parameters are specially important for constrained air-ground communications and for airborne inter-process communication. ADS-B and TIS-B periodicities are controlled by SURAIR and SURGND systems on the basis of the surrounding consumer needs and surveillance quality assurance.

## V. AIR SURVEILLANCE STRUCTURE AND ALGORITHMS

The structure of air surveillance system is depicted in Fig. 2.

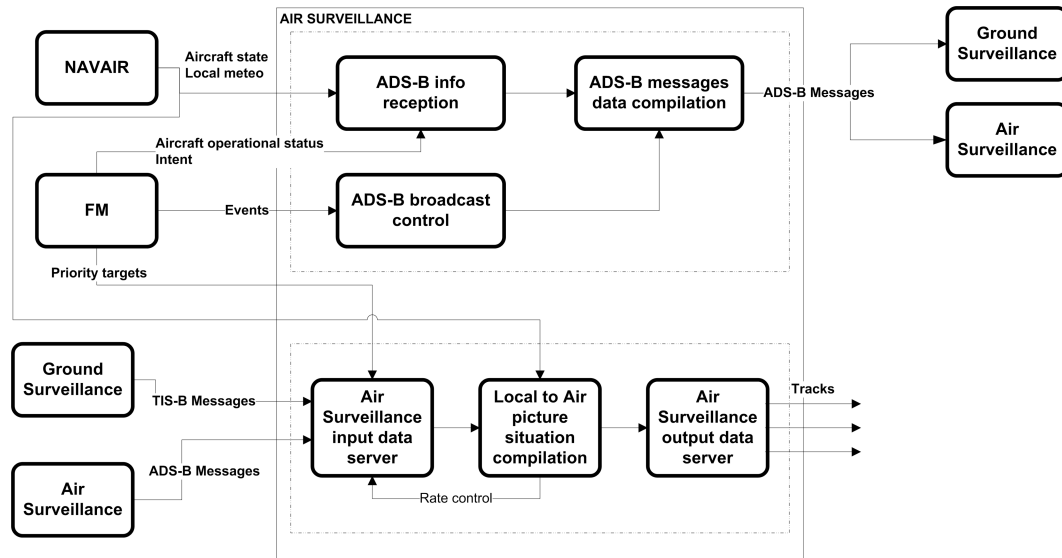


Fig. 2. Air Surveillance internal structure

It is mainly divided into two parts, to be described next.

### A) ADS-B compilation and broadcast

SURAIR receives ADS-B data from FM (callsign, intent, status) and NAVAIR (kinetic state, time, meteorological samples). In the case of NAVAIR data, the reception will be periodic with a high data rate, and data from FM will be received asynchronously, i.e. when it changes. SURAIR must maintain a copy of the last samples of each type of received data. ADS-B messages are broadcasted at a potentially variable data rate, depending on potentially time-changing FM requirements. Those requirements are linked to the presence of near aircraft and consequent increased data rates to enhance conflict detection procedures, and to the reduction of broadcast rates to manage communications and computational load.

NAVAIR will provide most of the information to be broadcasted, making use of its navigation and air system sensors, integrating inertial navigation and GNSS data to overcome integrity problems, but this issue is out of the scope of this paper. NAVAIR also provides flags in order to have a reference of the quality of the provided kinetic data, such as Navigation Accuracy Category (RTCA 260-a).

### B) Surrounding aircraft air surveillance

This function is in charge of obtaining the local-to-aircraft air picture. It contains three steps:

- Air surveillance input data server: receives ADS-B/TIS-B messages and removes TIS-B messages from every aircraft sending ADS-B information, and manages SURAIR computational load by removing messages (in a controlled way) in overload situation. Specially important here is the concept of priority targets, whose ADS-B or TIS-B must not be removed as they are specially important from the FM point of view.
- Air picture situation compilation, to be detailed bellow.

- Air surveillance output data server: the output data server block is in charge of communicating results of the air surveillance function to the FM. It updates periodically the track states, synchronized in time, to feed the FM.

Next we will detail Air picture situation compilation process, depicted in Fig. 3.

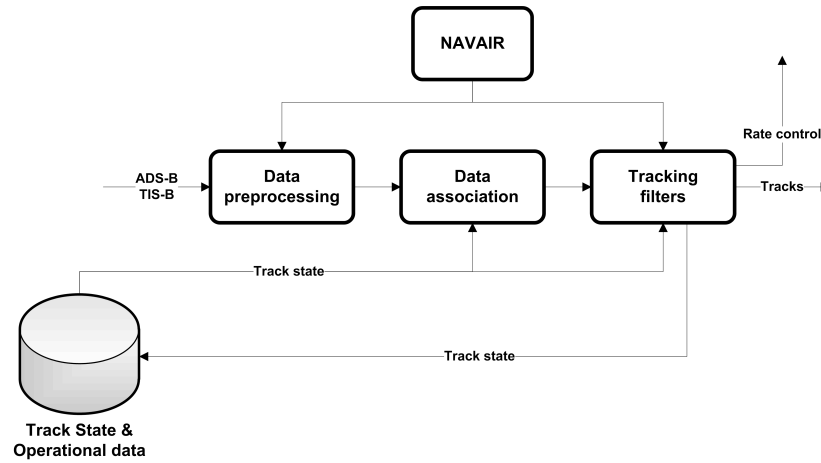


Fig. 3. Air Picture situation architecture

Pre-processing consists of the coordinate transformation and error covariance estimation for ADS-B kinetic messages. Tracking is performed in an auxiliary stereographic plane whose tangential point (tracking reference position) is a dynamically changing (every few minutes) position near the aircraft. All position and velocity measures are projected onto this plane.

The accuracy of ADS-B position and velocity reports will be expressed in tracking coordinates, taking into account the error models of ADS-B: Accuracy expressed typically following Navigation Accuracy Category (RTCA 260-a) will be translated to a measurement covariance matrix for horizontal position and a variance for vertical position. TIS-B messages will not be filtered, and therefore it is not necessary to assess their accuracy.

After preprocessing, measurement to track association must be performed. The association process among target reports (ADS-B or TIS-B) and tracks has been reduced to a code association (using the ICAO 24 bits address) protected through a maximum distance association gate. A track will be initiated once an ADS-B or TIS-B message with a new code is received. Track deletion procedure is based on track age (too large time from last track update). Additionally, means for converting TIS-B based tracks in ADS-B based tracks and vice versa are defined. Only 3D Position and ground velocity are considered for tracking. Other information, from different types of ADS-B messages, will be updated directly in the track state but not considered for tracking. There are independent filters for horizontal relative position and for geometric and barometric height. The horizontal tracking filter is one of Kalman type due to airborne low processing capabilities. It has a residual based manoeuvre detector, increasing acceleration variance in a piecewise constant white acceleration model [8] during a fixed time interval after manoeuvre detection. There are two independent vertical tracking Kalman filters used to process independently barometric and geometric heights measurements.



Based on the quality of the estimated track, tracking function computes and communicates to the surveillance input data server the data rate necessary to maintain track quality. Therefore the input data server may discard ADS-B messages coming from targets with high quality tracks, if they are not marked as high priority targets, to manage SURAIR behaviour in an overload situation.

## VI. GROUND SURVEILLANCE STRUCTURE AND ALGORITHMS

The Ground Surveillance architecture is depicted in Fig 4. In our experimental deployment it was just based on ADS-B measures, although any modern operational system such as AIRCON® is also capable to perform a fusion process incorporating radar (primary, secondary and Mode S) and WAM measurements to provide a unified output.

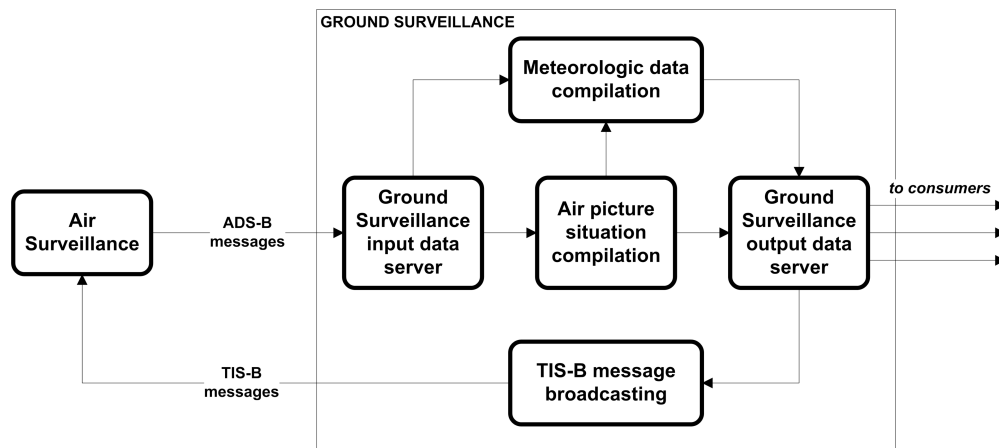


Fig. 4. SURGND Architecture

The main parts of SURGND are:

- **Ground Surveillance Input Data Server:** This subsystem is in charge of receiving ADS-B messages and discarding repeated messages, and of receiving other sensor measures. ADS-B measures are then provided to different subsystems within SURGND. ADS-B kinetic and status messages are provided to Air Picture Situation Compilation block while meteorological messages are provided to Meteorological Data Compilation.
- **The Air Picture situation block** executes the three central processes of Fig. 5. It is a system similar to SURAIR Air Situation Picture Compilation, but with the following main differences:
  - It does not process intent information messages.
  - It has no need to change the tracking reference position along time, as it is fixed for ground surveillance.
  - Due to additional computational resources, pre-processing, data association and tracking filters are enhanced versions of those in SURAIR.

- **Meteorological Data Compilation:** SURGND receives Meteorological ADS-B messages, and sends meteorological samples to DMET. Those samples do not have any information regarding the identification of the aircraft providing the measure, but they provide a position and time to enable DMET exploitation of the meteorological sample in a time-varying 3D weather model. This subsystem obtains the sample reference position from Air Picture Situation tracks.
- **Ground Surveillance Output Data Server.** The output data server block is in charge of periodically communicating the results of the surveillance function to other ground systems.
- **TIS-B Control and message broadcasting,** from current tracks, managing publication period to control SURGND load.

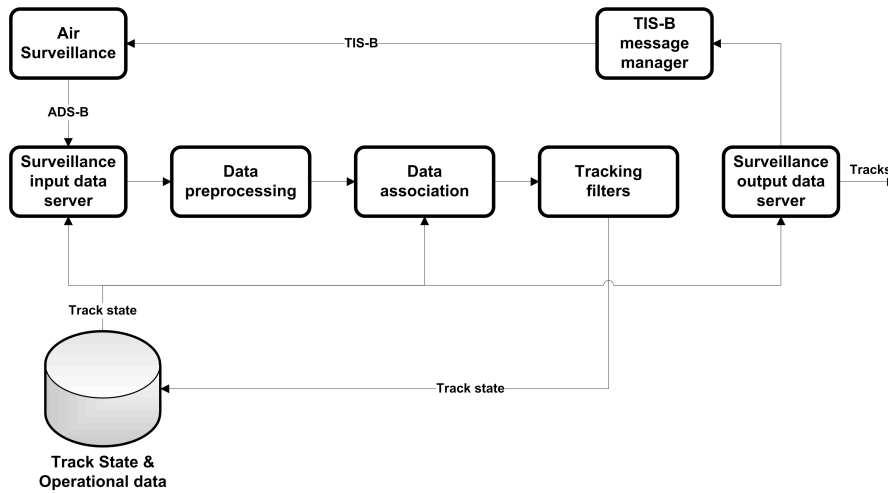


Fig. 5. Air Picture situation architecture

The tracking filter is the central process in SURGND. This filter processes the time ordered sequence of ADS-B reports from the same target, and may also perform track-based fusion of ADS-B with other sensors measures. There are independent filters for horizontal relative position and for geometric and barometric height. The horizontal tracking filter is one of the Interactive Multiple Model (IMM [9]) type: a set of Kalman filters adapted to different movement models whose outputs are combined as a function of residual error (differences between position predicted by the filter and new available measures). This filter has many well-known characteristics: i) it has a quickly response to target manoeuvres, ii) it has an automatic estimation of the MOF and iii) it maintains an estimation of the quality of the estimated state. Additionally, there are two independent Kalman vertical tracking filters: for barometric and geometric heights respectively. Both vertical and horizontal tracking filters can process position and speed measurements.

## VII. Surveillance performance metrics definition and experimental deployment

The Surveillance Performance Metrics evaluated in this paper are mainly of two types:

- Delays in the Navigation/Surveillance chain.

- Tracking filter accuracy, both for SURAIR and SURGND.

Both simulations and analysis of real surveillance data were used to obtain those assessments. For both kinds of evaluations specific tools have been developed, following the ideas described in [12]. The evaluation procedures are detailed for ADS-B in Fig. 6 and Fig. 7. Similar approaches have been used for the evaluation of TIS-B based SURAIR performance, although in this case accuracy was not evaluated as it is dependent on SURGND quality, and specifically of the other sensors (Mode S, WAM) available.

With simulated scenarios, we can have a fine control of the aircraft trajectories and an exact calculation of tracking error statistics in controlled environments. Meanwhile, real flight scenarios will be more useful for realistic evaluation of communication and real time synchronization effects of ADS-B/TIS-B over surveillance: they are based on the interpolation of navigation or ADS-B data to calculate sampled trajectories to be used as “ground truth” for accuracy assessment.

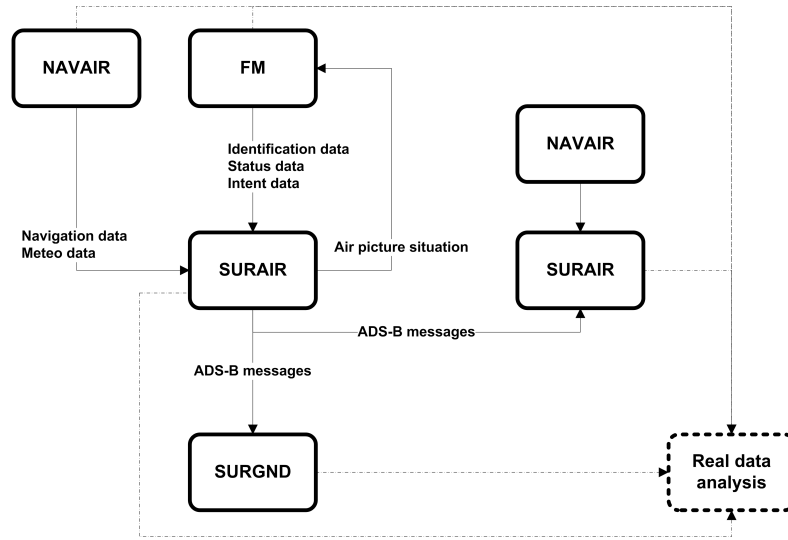


Fig. 6. ADS-B assessment with real data

In Fig. 6, the procedure to perform ADS-B real flight data analysis is depicted. Data in the aircraft, including a list of all messages interchanged by SURAIR, navigation data, and FM data, are saved in real time for later analysis. On ground, SURGND will also record all messages received and the track states.

Offline real data analysis tools need to extract the SURAIR, NAVAIR and FM data from airborne recordings. Then, using these data, they will obtain a reference reconstruction of the aircraft trajectory (mainly based on navigation data, if available, or otherwise on ADS-B messages smoothing). ADS-B measurement accuracy can be measured comparing reference trajectories and kinetic measures. Meanwhile, SURGND and SURAIR tracking accuracy are measured comparing their respective tracks with the corresponding reconstructed trajectories.

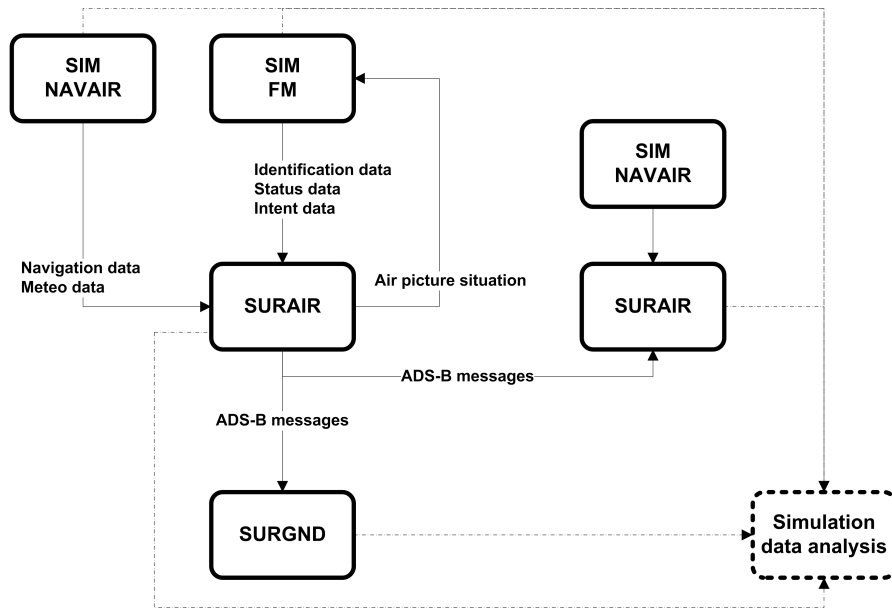


Fig. 7. ADS-B assessment using simulation data

Fig. 7 summarizes ADS-B performance analysis based on simulation. The idea here is substituting the actual NAVAIR and FM systems by simulated systems. SIMNAVAIR will calculate an ideal test trajectory, and will corrupt measurements from this ideal trajectory with navigation error, in order to simulate a realistic navigation measurement process. SIMNAVAIR will also record sampled measures of the ideal trajectory. FM will be simulated through SIMFM system, just to define an aircraft intent, status and identification needed to obtain statistics regarding communication. The same pieces of data as in real flight recordings, in the same formats, will be stored both at airborne and at SURGND recordings.

Simulated data analysis is performed using the same techniques as in real data analysis. The only difference will appear in the reconstruction phase, which does not need to perform any smoothing but just an interpolation of ideal trajectory samples provided by SIMNAVAIR.

## VIII. Simulated and Experimental results

Many different scenarios have been analysed. Some representative results both from SURGND and SURAIR simulated results are summarized next.

### A) Simulated data analysis

A simulated scenario is depicted in Fig. 8, where two aircraft follow encounter geometry with manoeuvres with transversal accelerations in the order of  $3 \text{ m/s}^2$ . Trajectory A is the one in the north, while trajectory B is in the south.

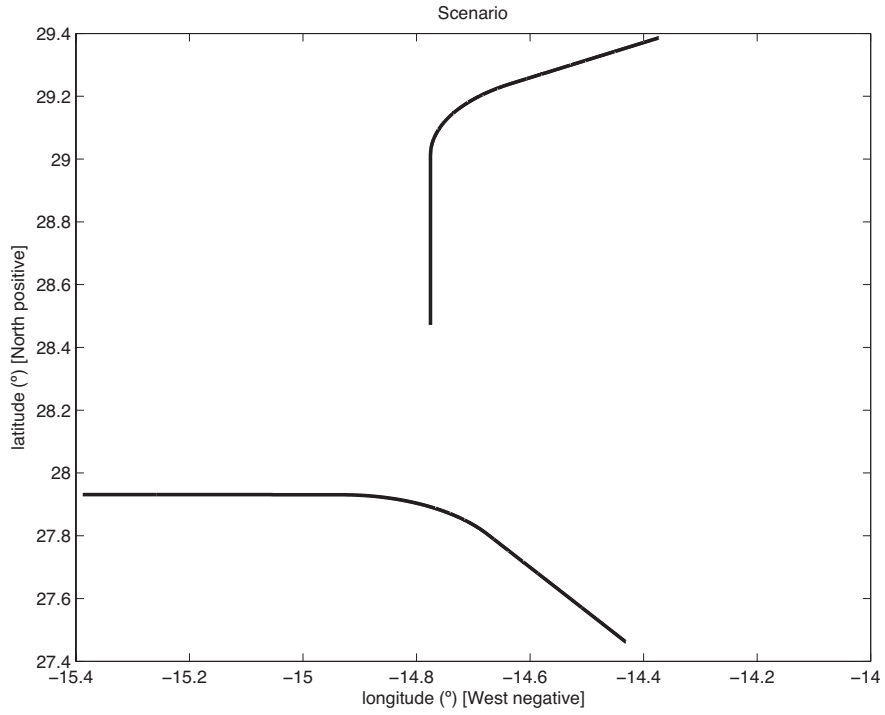


Fig. 8. ADS-B simulation scenario using simulation data

The time varying RMS of the error, calculated through Monte Carlo simulation can be seen, for SURGND, in Fig. 9. Dotted lines represent the measurement error while continuous lines are used to depict filtered error. These results were obtained for the case of GPS with no differential corrections, assuming around 30 m standard error in longitude and latitude and around 0.05 m/s velocity standard error in Cartesian coordinates, modelled as white noise (which is a quite rough GPS error model just used to tune the filters).

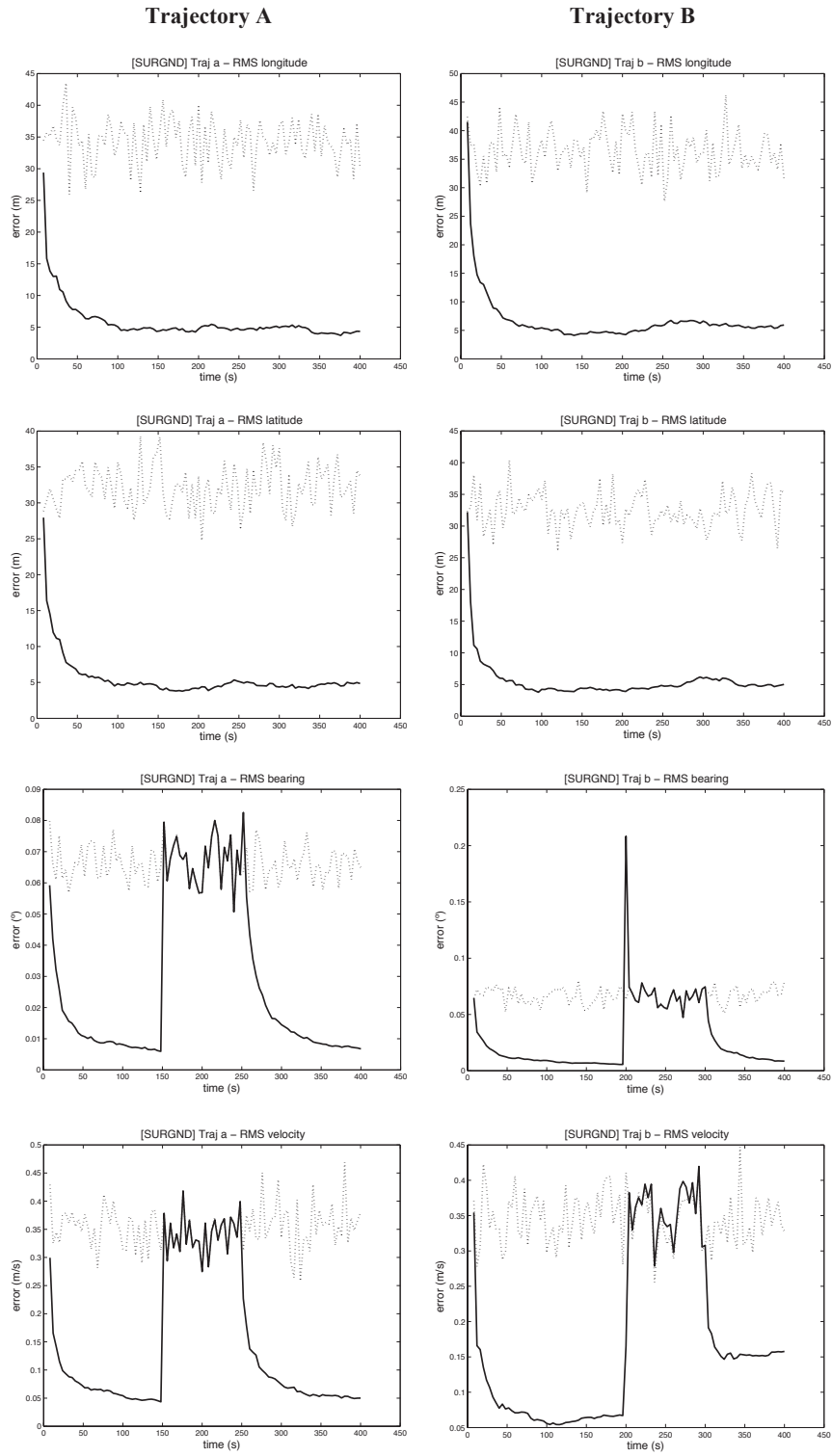


Fig. 9. SURGND Surveillance: RMS results (FOM pos=7 vel=3)

From this simulation it is clear that the filter reduces both position and velocity errors to almost negligible values in non-manoeuving conditions. In manoeuvring conditions the filter is able to maintain velocity errors almost equivalent to those of measures while improving position estimates (in fact, with respect to position, the estimate maintains its quality even for manoeuvring conditions).

SURAIR errors are slightly bigger in general, due to the use of a Kalman filter instead of an IMM filter, especially for the velocity magnitude. In addition there is a bias term of up to  $0.3^\circ$  appearing in bearing, due to the mismatch between the local planes of both aircraft. When the two aircraft become nearer, this bias becomes negligible.

## B) Real data analysis

Simulated data may serve to perform simplified evaluations of surveillance systems quality, but in order to gain accurate knowledge of the real quality of the system real data must be used. In the following section results from a representative flight test are described. Fig. 10 depicts the real scenario, along with the measurements and reconstructed flight projected in the horizontal plane (X axis pointing towards east, and Y axis towards north). The scale of both images is not equal, which accounts for the deformation. It is a complete flight starting and ending at Marugan aerodrome (near Segovia, Spain). ADS-B kinematic measures were obtained every 2 seconds.

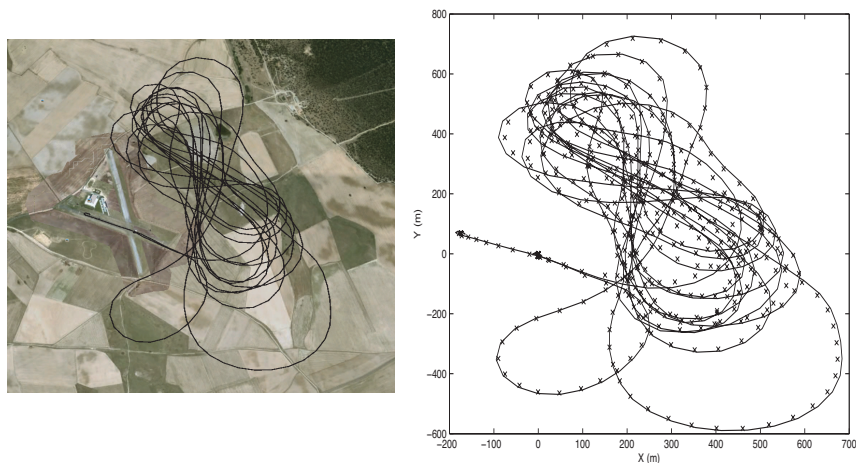


Fig. 10. SURGND Surveillance: Real data scenario and reconstruction

Fig. 11 and Fig. 12 show position and velocity errors, both from raw measurements (crosses) and SURGND tracks (lines).

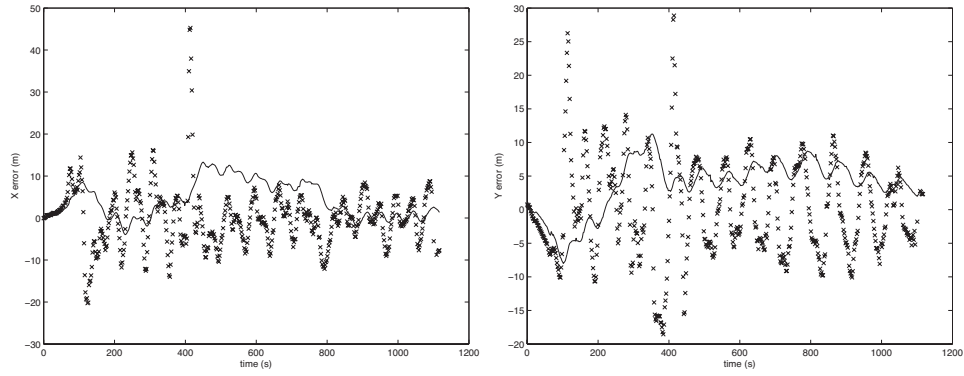


Fig. 11. SURGND Surveillance: X and Y errors

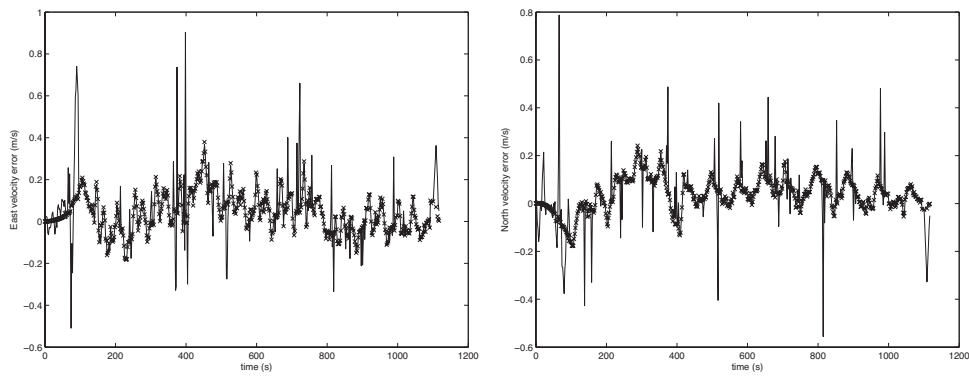


Fig. 12. SURGND Surveillance: East and North velocity components errors

From those results it is possible to conclude that:

- Measures suffer correlated errors, either due to lack of stability of aircraft flight or to navigation data processing, which is not only based on pure GPS measurements but also on smoothing processes taking into account other airborne sensors.
- SURGND (and SURAIR) obtains a better and more stable estimate of smoothed position than raw measures, especially with respect to maximum errors.
- Measured velocity and filtered velocity are almost equal most of the times, although in the times related to the “detection” of a manoeuvring condition by IMM, this filter tends to develop slightly higher biases. The key aspect here is velocity is a considered as a very good measurement by the filter, which tends to assume it is better not to smooth it.

Finally, regarding messages delays, in the central part of this flight the results in Fig. 13 were obtained.



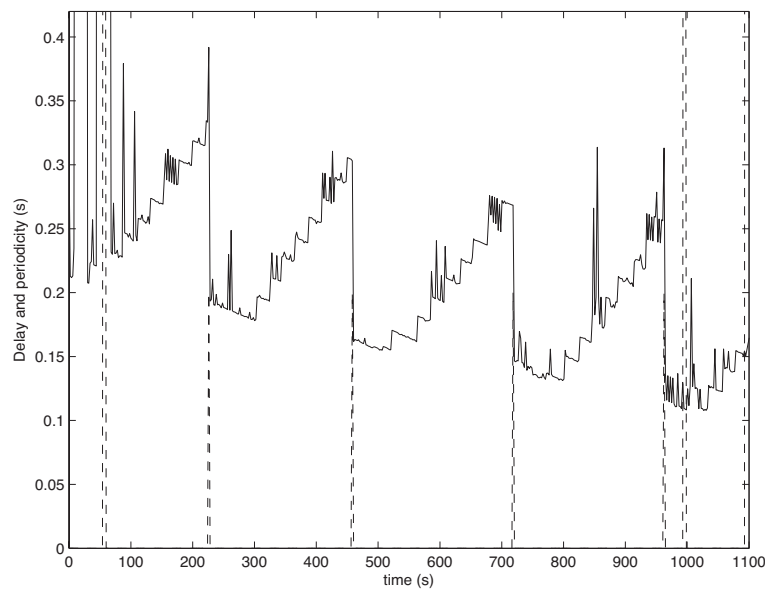


Fig. 13. SURGND Surveillance: Filtering delay and measurement periodicity error

The delay between measurement compilation at NAVAIR and processing at SURGND is depicted in continuous line. The delay ranges most of the time between 0.15 and 0.35. This is due to the combination of several effects:

- A mean communication delay in the order of 0.15 seconds, slightly higher than the simulated one, which was in the order of 0.12 seconds.
- Random jittering terms due to communications.
- A drift between GPS time and asynchronous SURAIR activation time. NAVAIR GPS measures are obtained with a periodicity of 0.2 seconds. So, depending on the relative phases of both clocks the error changes, this accounts for an additional delay between 0 and 0.2 seconds.

This later effect can be observed by measuring a periodicity error as the difference between ADS-B messages timestamp first difference and the nominal 2 seconds period. It is depicted in Fig. 13 as discontinuous line. Every 100 to 300 seconds the actual period changes from 2 seconds to 2.2 seconds, as the drift makes SURAIR jump over a GPS sample and at the same time the complete communication delay is reduced.

Finally, although not visible in the presented results, while the aircraft was on aerodrome surface there was a not-negligible probability of losing measurements or receiving them with much higher delay. The problem was related with communication overload conditions prior to aircraft take off, where many initialization data was provided to the aircraft.

## IX. CONCLUSION AND FUTURE WORK

This paper details the experimental development of an air-ground surveillance system integrated in ATLANTIDA system. Our simulated and real data shows it will fulfil even the most demanding surveillance accuracy requirements (see, for instance [13]). Typical requirements regarding update rate for the controllers are in the range of one update every 4-5 seconds, and radar based systems surveillance is not homogeneous in radar coverage, with typical error RMS for non-maneuvring conditions in the order of 100 meters and in the order of 250-500 meters for manoeuvring conditions. Bearing error RMS in the order of  $10^\circ$  in manoeuvres is also typical.

Some key features of the proposed experimental deployment are:

- Support for new data types of interest for TBO using advanced trajectory prediction infrastructures, especially for air-to-air trajectory negotiation, such as intent, dynamic state, aircraft configuration, etc.
- Air inclusive SWIM integrated communications, with ADS-B using a safer and more predictable communication channel.
- Integration in a complete prototype ATM system (ATLANTIDA). Specifically, ground surveillance was integrated in an adapted version of operational surveillance system (AIRCON®) and with traffic management tools.
- Experimental orientation, enabling data recording for analysis, integration in simulated environment, etc.
- Air surveillance integrated in a low cost PC-based avionics platform including a Satellite based navigation system, a fully automated Flight Management System, data recording support, an emergency and alert support system, among other features.

Regarding future research lines, the following ideas may drive future enhancements of aircraft surveillance using a SWIM infrastructure:

- Extension of air surveillance applications, especially those related to coordinated manoeuvres and delegation of responsibility to aircraft pilots.
- Extension of the use of intent information to reduce prediction error in manoeuvres. Reduced versions of aircraft intent could be used for this extrapolation, enabling higher performance short-term conflict alerts. Of course, this demands the higher integrity in the ADS-B provided intent, which should be completely coherent with actual operations performed by FM to control the aircraft operation and should enable an accurate extrapolation of the trajectory to short time intervals. Aircraft Intent Description Language, as described in [11], has demonstrated in ATLANTIDA project to be a suitable intent description format for this and other trajectory prediction applications.

- Increase of adaptability of surveillance to context and traffic information. Mechanisms as the one proposed in ATLANTIDA to control periodicity of messages, coupled with management procedures relating surveillance performance and higher level systems requirements (short term conflict alerts, flight plan conformance monitoring, etc.), might adapt ADS-B periods to current traffic situation. In addition, potentially problematic areas could have increased data rates.
- Definition of enhanced ground based and air based short-term alerting systems to enhance overall safety of traffic. It should be emphasised, though, that from a safety perspective it is important to maintain Airborne Collision Avoidance System (ACAS), which could be improved using ADS-B measurements, as an independent on-board safety function, fully decoupled from short-term conflict alert in Ground ATC.

Finally, it is clear ADS-B must be improved to include new information supporting accurate trajectory prediction to enable new applications. The final format of the intent/trajectory information to be interchanged is directly related to the negotiation procedures in the ATM system. In addition, it is clear that the use of air inclusive SWIM does not preclude the possibility to have high quality surveillance. The additional overload in communications can be compensated by increased reliability and capability to manage the actual load of the communication channel.

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## Abbreviations

<b>ADS-B</b>	Automatic Dependent Surveillance - Broadcast
<b>ACAS</b>	Airborne Collision Avoidance System
<b>ADS-C</b>	Automatic Dependent Surveillance - Contract
<b>ASAS</b>	Airborne Separation Assurance Systems
<b>ASTERIX</b>	All Purpose Structured Eurocontrol Surveillance Information Exchange
<b>ATM</b>	Air Traffic Management
<b>CNS</b>	Communication/Navigation/Surveillance
<b>CORBA</b>	Common Object Request Broker Architecture
<b>DDS</b>	Data Distribution Service
<b>DMET</b>	Meteorologic System (ATLANTIDA)
<b>FHSS</b>	Frequency Hoping Spread Spectrum
<b>FM</b>	Flight Manager (ATLANTIDA)
<b>GNSS</b>	Global Navigation Satellite System
<b>GPS</b>	Global Positioning System
<b>ICAO</b>	International Civil Aviation Organization
<b>IMM</b>	Interactive Multiple Model
<b>NAVAIR</b>	On board Navigation (ATLANTIDA)
<b>QoS</b>	Quality of Service
<b>RFM</b>	Remote Flight Manager (ATLANTIDA)
<b>RMS</b>	Root Mean Square
<b>SIMFM</b>	Simulated Flight Manager (ATLANTIDA)
<b>SIMNAVAIR</b>	Simulated On board Navigation (ATLANTIDA)
<b>SURAIR</b>	Air Surveillance (ATLANTIDA)
<b>SURGND</b>	Ground Surveillance (ATLANTIDA)

<b>SWIM</b>	System Wide Information Management
<b>TBO</b>	Trajectory Based Operations
<b>TDMA</b>	Time Division Multiplex Access
<b>TIS-B</b>	Traffic Information System-Broadcast
<b>TM</b>	Traffic Manager (ATLANTIDA)
<b>UAS</b>	Unmanned Aircraft System
<b>UAT</b>	Universal Access Transceiver
<b>VDL</b>	VHF data link
<b>WAM</b>	Wide Area Multilateration

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